DEVELOPMENT OF A SENSOR-BASED STRUCTURAL INTEGRITY MEASUREMENT TECHNIQUE FOR POTENTIAL APPLICATION TO MISSILE CASINGS

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ABSTRACT

Missile structures pose a unique challenge for deploying structural health monitoring (SHM) and condition based maintenance (CBM) technologies and protocols. The inventory of missiles is relatively large, varied, and often missiles are held in storage for extended periods of time. However, when needed, the overall functionality and integrity of the missile system and its components must be fully ready and operational. Our present work has examined the development of a practical, low cost, low power scheme for assessing the structural integrity of missile systems. It is one of the first known efforts to integrate sensor data with structural analytic and numerical models to provide not only a location and history of adverse loading events, but also an estimate of stiffness degradation in the structural casing. S2 glass/epoxy composite cylinders were chosen because they provide an observable means of witnessing damage for correlation purposes.

1. INTRODUCTION

Missiles play an important role in the Army's overall arsenal of weapon systems and their proper storage, transport, and deployment are increasingly coupled as threat scenarios become more complex. Safely and rapidly transporting missiles to and from their required location presents not only a logistics issue, but could potentially affect the integrity and operation of the missile and launch systems if they are exposed to adverse loading and impact events. After transport, the decision to launch relies on several pieces of information. Fundamental to this array of information is the confidence that the missile system is "healthy" enough to launch – i.e., no sub-system failures, faults, or impairments of missile body or launch infrastructure. Finally, the storage of missiles poses another concern; the systems may remain dormant for indefinite periods of time and it is important to determine if any damage or degradation may have occurred.

The missile platform we used as a basis for this study was the future Non-Line of Sight-Launch System NLOS-LS, (i.e. "Net Fires") as part of the Future Combat System (FCS). NLOS-LS are a cluster of containerized missile battery, much like an arsenal-in-a-box, which is highly field-deployable and must be rugged. Our focus was primarily on the NLOS-LS' precision attack missile (PAM) (at the time of this study the PAM was still in the design concept stage) because it incorporates a solid rocket motor propulsion system. We focused specifically on the missile motor case structure. It is essential to determine the state of "health" and operability of each missile for its proposed mission. Figure 1 illustrates the containerized version of the NLOS-LS and a PAM missile concept drawing.

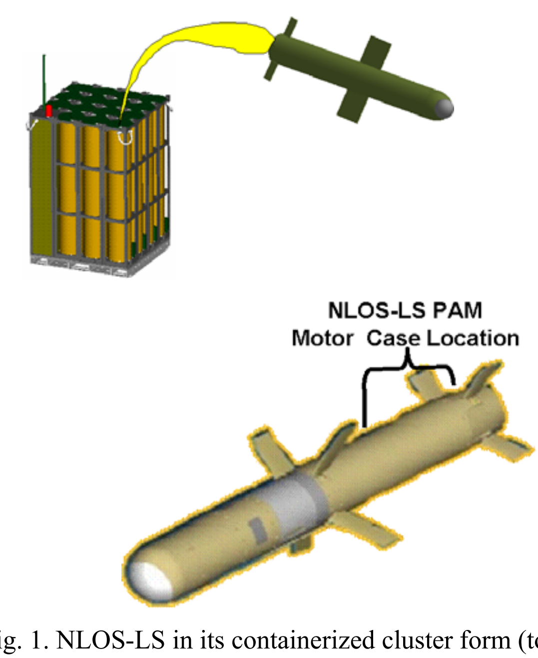

Fig. 1. NLOS-LS in its containerized cluster form (top); conceptual drawing of the PAM (bottom).

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Composite materials are attractive for constructing missile bodies. The ability to customize the strength to weight ratios of composite materials is making them the preferred choice for payload, range, launch, and other criteria. The associated high strength to weight ratios, compared to homogeneous metallic materials, will significantly reduce the logistics burden for transporting and deploying these systems. However, composite materials tend to be more sensitive to certain types of damage than conventional isotropic materials such as aluminum. Given that a missile contains propellant and possibly a warhead, the safe and effective operation of the missile is critical. A potential approach for ensuring the integrity of the missile structure is to consider the use of sensor-based structural health monitoring (SHM) technology. SHM has been successfully used elsewhere (Ackers et al., 2006) and can serve as a source of data for condition-based maintenance.

2. BACKGROUND

Despite these advantages, composites are susceptible to a variety of damage mechanisms including fiber breakage, delaminations, matrix cracking, and environmental degradation as illustrated in Figure 2. Potential adverse loading and damage events and conditions are depicted in Figure 3, such as during firings, airlift and cargo transport, ground offloading and transport, and storage facility mishaps.

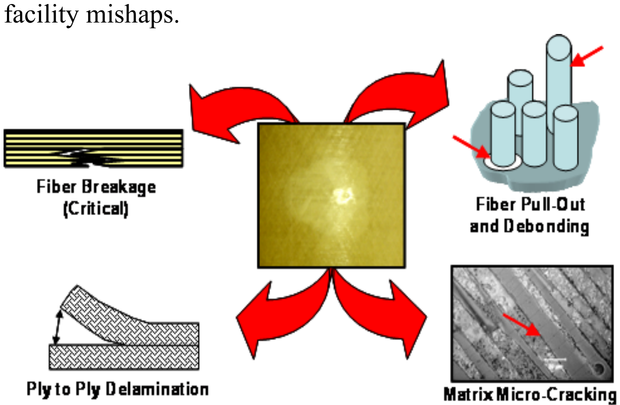

Fig. 2. Typical types of damage mechanisms sustained by a composite casing.

Consequently, the ability of these composite-based weapons to operate after sustaining inadvertent impact loads during shipping, transport, and long-term storage in addition to variations in environmental conditions (e.g., temperature, humidity, and solar radiation) must be assessed continually to ensure the readiness of such weapons. It has been shown that 85% of all damage in the field is due to some form of sustained impact. For example, downwash from helicopter main rotor blades during take-offs and landings can cause debris to impact missile bodies before they are utilized. If damage is sustained in the missile's motor case region, these impacts can result in over a 30% reduction in burst strength leading to inoperability of the weapon or in worst case scenarios catastrophic failure of the motor case during ignition launch. A near real-time SHM system is needed to provide military personnel and weapon maintainers with instant feedback on the health of each system before it is deployed.

Fig. 3a. Firing: imposes short extreme conditions

Fig. 3b. Airlift and cargo transport

Fig. 3c. Offloading and ground transport

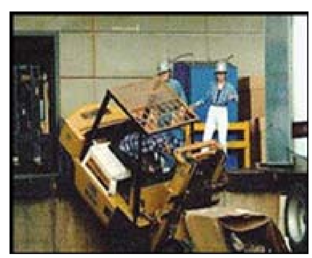

Fig. 3d. Storage facility mishaps

Fig. 3. Potential damage source

This work aims to develop a complementary set of data interrogation methodologies to characterize the presence of damage and quantify the resulting strength (stiffness) reduction in impact damaged S-2 glass/epoxy canisters. Initially, the inherent variability of the baseline (healthy) canisters under different test conditions was investigated to assess the feasibility of diagnosing impact damage in real-world operational scenarios.

3. DAMAGE DETECTION TECHNOLOGY

Transmissibility is defined as a simple ratio of two frequency response measurements (Johnson and Adams 2002). This measurement provides an indication of damage along the path connecting those two points. This information is then used in a percent error formulation over a given frequency range to obtain the final damage index (DI). The level of the damage was quantified using the embedded sensitivity function (Johnson et al., 2005), which is based on a finite difference formulation and provides a measure of the effective stiffness change. Finally, in order to locate the damage, a frequency wave propagation based method was employed. By using a phased sensor array, the arrival time required for the wave to travel from the actuator to each sensor is used to determine the direction in which the signal strength from the damage area is a maximum. Using the steering angle for a pair of sensors, the location of the damage was triangulated. This beamforming methodology is illustrated below in Figure 4.

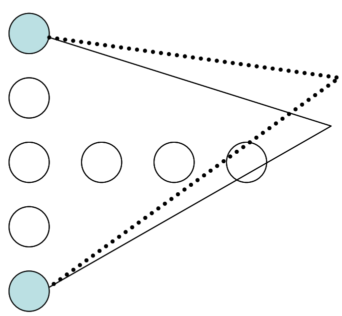

Fig. 4. Beamforming technology

4. EXPERIMENT

Test specimens consisted of filament wound S2 glass/epoxy composite tube sections with wall thicknesses typical for missile bodies. Three specimens received impact loads of 1, 3 and 5 foot pounds, respectively, and are shown in Figure 5. Due to the translucency of the material the impacted areas were clearly visible. Yet, it is important to define a benchmark for assessing the ability of damage detection techniques to locate and measure damage. As such, the S2 glass tube samples were subjected to more conventional nondestructive evaluation (NDE) techniques, which included conventional pulse echo ultrasonic testing (UT) and a unique thermal imaging inspection method. Both NDE techniques also clearly showed the damage within the tube structures with excellent correlation. In addition, three undamaged tube specimens were also used; sensor data retrieved from these specimens were averaged and used as baseline values.

1 ft-lb 3 ft-lbs 5 ft-lbs

Fig. 5. Impacted tube specimen

UT is a basic NDE technique utilizing ultrasound to detect damage within a material. UT is primarily conducted by immersing the test article into a water tank and then performing the ultrasound scan. Anomalies within the test article change the velocity of the ultrasound as it passes through the part to a receiver. This data is further processed for easy interpretation, such as in Figure 6, which shows a colorized UT C-scan image (enlarged view) of the 3 ft-lb impact damaged tube specimen.

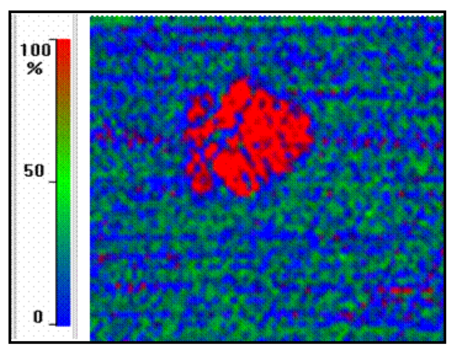

Fig. 6. Ultrasonic imaging of 3 ft-lb impact damaged tube specimen

In addition, a unique thermal imaging technique was developed to inspect the specimens for damage. A tube specimen was placed on a motorized rotating platform while heat energy from a 1000 watt quartz lamp irradiated the surface. An infrared (IR) thermal imaging camera was used to scan the heat emitted from the item under test. Anomalies/flaws change the heat flow through the composite. The IR camera can detect these subtle thermal contrast differences, such as the damage caused by the impact as shown in Figure 7. Due to the camera's wide angle field-of-view, large areas can be inspected in relatively short times. Incorporating the motorized platform, an entire tube specimen was inspected in well under a minute using the thermal imaging technique.

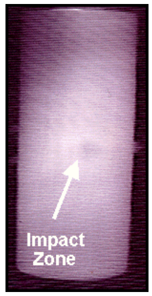

Fig. 7. Infrared imaging of the 3 ft-lb impact damaged tube specimen

In the health monitoring experiments, the necessary frequency response functions were obtained for both undamaged and damaged canisters. Given the cylindrical structure of the specimens, two PCB 333B32 sensors were positioned at either end of the cylinder. The response data was acquired by performing modal testing to simulate ambient transportation vibrations using a PCB 086C03 modal impact hammer. An Agilent VXI system running the Multiple Reference Impact Testing software was used to acquire data.

The wave propagation-based approach to localize damage used an algorithm that sums the time-delayed response acquired using an array of sensors as shown in Figure 8. A 5 wave modulated Hanning windowed sinusoidal pulse, centered at 10 and 20 kHz, was generated using an Agilent 33220A arbitrary waveform generator. The signal was imparted to the structure using a 402815 PI ceramic stack actuator. Ten low sensitivity, high frequency accelerometers (PCB U352C22) were arranged in a T-array with an 16.6 mm offset between adjacent sensors. This spacing was chosen to be equal to half the wavelength of the excitation signal. The corresponding response signals were measured using a Tektronix TDS5054B-NV-T digital oscilloscope. The wave speed at 20 kHz was determined to be 440 m/s after accounting for the angular variation. A lumped mass was placed on the cylinder to simulate the effects of damage; the impact damage was much larger and was easily located. The small mass addition was used to simulate small damage levels.

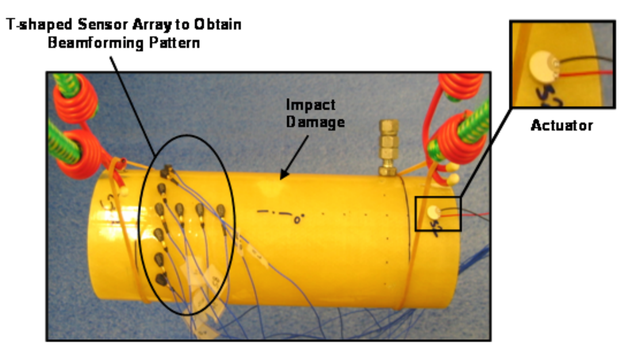

Fig. 8. Instrumented tube

5. ANALYSIS

In order to link the estimated health monitoring stiffness reductions to strength reductions, a finite element model was created. The purpose of the finite element analysis was to estimate the damage associated with each of the specified impact energies using the estimated stiffness reductions resulting in an estimated strength reduction. The finite element model utilized shell elements with composite material properties. The properties of the composite lay-up are shown in Table 1 and the ply properties used for fiberglass are shown in Table 2. The elements used are reduced integration elements for improved transverse shear approximation. The finite element model with deformation contours is shown in Figure 9.

Table 1. Composite lay-up

Thickness (in)	Material Orientation (degrees)	
0.008	90	Tube OD
0.008	90	
0.008	30	
0.008	-30	
0.008	90	
0.008	90	
0.008	30	
0.008	-30	Tube ID

Table 2. Fiberglass ply properties

E_{11}	5.95E6 psi
E_{22}	1.3E6 psi
ν_{22}	0.28
G_{12}	0.86E6 psi
G_{13}	0.48E6 psi
G_{23}	0.48E6 psi

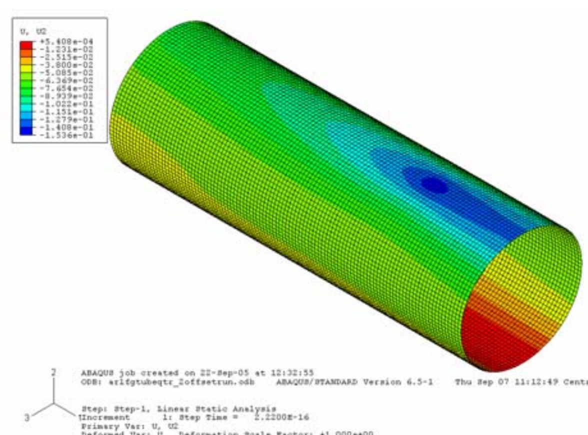

Fig. 9. Finite element model with deformation contours

The model was constrained along the bottom against vertical motion and along one side to restrain lateral motion and on one end to restrain axial motion. Three separate load cases were analyzed applying a vertical force at three locations along the length. The force locations were at the middle of the tube, the quarter point and at the end. The displacements at the load location were used to approximate the tube stiffness. This information provided baseline stiffness for the correlation of estimated stiffness reductions to strength reductions. The finite element model was then used to approximate the damage associated with the estimated health monitoring stiffness reductions. This was accomplished by removing layers until the appropriate stiffness reduction is predicted by the finite element analysis.

6. RESULTS AND DISCUSSION

Using the transmissibility and embedded sensitivity formulations, it was possible to detect damage and quantify damage by looking at the response between 1.5 kHz and 2 kHz. These results are presented in Table 3. It can be seen that the damage index for the damaged canisters always exceeds one and that there is a direct correlation between damage level and index value. Based on the stiffness reductions presented in Table 3 for the two different impact energy levels and a measured static stiffness, it was determined that the 1ft-lb impact resulted in an overall 6.8% reduction in static stiffness, while the 5ft-lb impact resulted in a 27.3% reduction.

Table 3. Damage detection and quantification results

Canister	Damage Index (1.5-2 kHz)	Change in K (lb/in)
Baseline	.79	N/A
1 ft-lb impact	1.17	60
5 ft-lb impact	1.44	240

Damage Localization:

Figure 10 shows the results obtained for the damage localization analysis using beamforming. The damage is located at (130, 37) mm and at angular positions of 49^o and 352^0 with respect to the two reference sensors. The damage was estimated to be at (116, 27) mm and at angular positions of 51^o and 341^o with respect to the two reference sensors. The deviation between the estimated and actual damage locations was due to the sensitivity of the location to small changes in steering angle. An error region (+/- 4^0) is also shown in Figure 10.

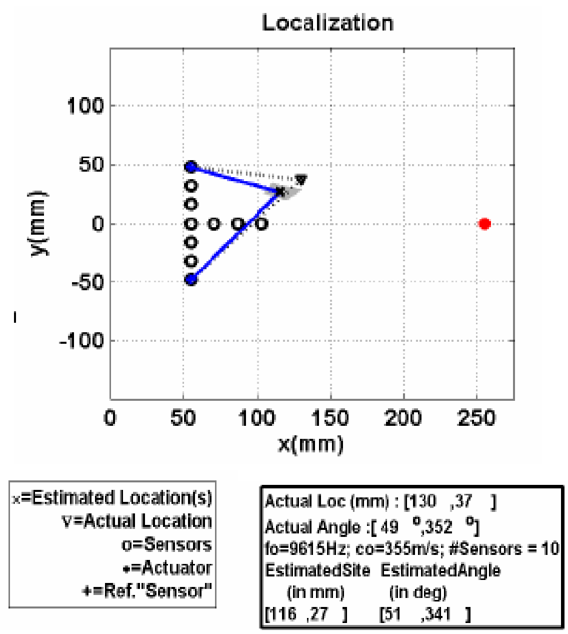

Fig. 10. Damage localization

The finite element analysis predicted stiffness results for the baseline tube is shown in Table 4. The stiffness reductions determined from the embedded sensitivity method shown in Table 3 may be considered average along the length of the tube. As shown in Table 4, the mid and quarter stiffness are about the same, but the end is much lower. In order to bound the stiffness reduction and damage approximation, the finite element stiffness reductions were performed at both the quarter and end points. Fiberglass epoxy composites are stronger in tension than in compression and at peak deflection during an impact event the outer hoop layers will be in compression and the inner layers in tension. Therefore, to approximate the stiffness reduction and damage, the outer hoop layers were removed. In addition, because these tubes are open-ended the failure mode of interest will be hoop failure.

Table 4. Finite element baseline stiffness

Load Location	Stiffness (lb/in)
Mid	1179
Quarter	1078
End	583

The approximate residual strength can be estimated by the remaining undamaged hoop layers. The undamaged fiberglass tube contains about 0.032 inches of hoop fibers. Table 5 summarizes the finite element stiffness reduction and damage approximation. Figure 11 shows the estimated residual strength reduction using the embedded sensitivity function estimates of reductions in stiffness.

Table 5. Finite element approximation of stiffness reduction and residual strength

Location	Impact Energy (ft-lb)	Stiffness Reduction (lb/in)	Hoop Thickness Removed (in)	Residual Strength (% of Original)
Quarter	1	60	0.0013	0.96
Quarter	5	250	0.0057	0.82
End	1	60	0.0025	0.92
End	5	250	0.0110	0.65

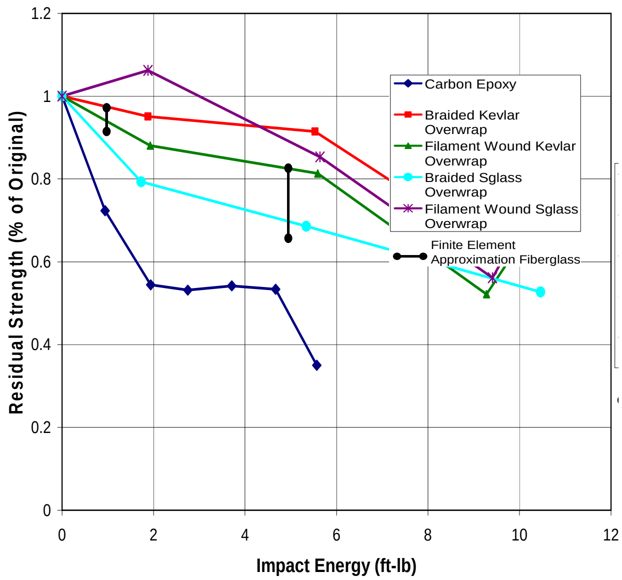

Fig. 11. Estimate residual strength using embedded sensitivity function.

7. CONCLUSIONS

This work has successfully demonstrated the application of a low power, low cost sensor-based structural health monitoring technique for detecting damage and identifying the location and extent of damage in composite cylinders. The cylinder materials and geometries were representative of the type of structure that will likely be used in the NLOS missile body. The damage detection technology provides a means to quantify reductions in strength and determine the precise location of the damage. This technology is one of the first examples of a health monitoring approach for quantifying damage and locating damage using relatively few sensors. Finite element models were used to model the effects of these stiffness reductions on burst strength.

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